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MODELING AND SIMULATION OF MORTAR FIN TOOLING USING CYCLIC SYMMETRY

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14. ABSTRACT

Cyclic symmetry is a method in finite element analysis that allows for the simulation of an entire cyclically symmetrical structure based on a model of one repeating sector. The reduction of model size obtained using cyclic symmetry can significantly reduce computational cost. This technique was employed to optimize the three pronged tooling design used to assemble mortar fins to the mortar body. Using cyclic symmetry, only one-third of the model was needed. The software package Abaqus Standard (implicit) was used for this nonlinear, static analysis. Results were compared to a 360-deg model. Cyclic symmetry reduced the computation time by more than four times without resulting in a loss of accuracy.

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A structure with a basic unit repeated around an axis can be described as exhibiting cyclic symmetry. Examples of common objects with cyclic symmetry include fans and turbines. If the geometry and loads of a model can be patterned cyclically, only one sector needs to be modeled in a finite element analysis (FEA) to evaluate the behavior of the whole structure. Because using the cyclic symmetry option in a FEA reduces the model size, the FEA requires less time to run and uses less computer resources.

The tooling process used to assemble 81-mm M24 mortar cartridge fins onto the mortar body has a geometry and loading pattern suitable for cyclic geometry. The fins are a two-piece design, consisting of aluminum fins press fit onto an aluminum housing (fig. 1). A three pronged tooling device is used to thread the fin assembly onto the mortar body. A study was conducted to determine how far from the longitudinal axis the tool contact point could be located. The further the contact points could be located from the center, the lower the cost of the tooling. Tooling configurations that would cause the fins to undergo plastic deformation away from the contact area would be considered unacceptable.

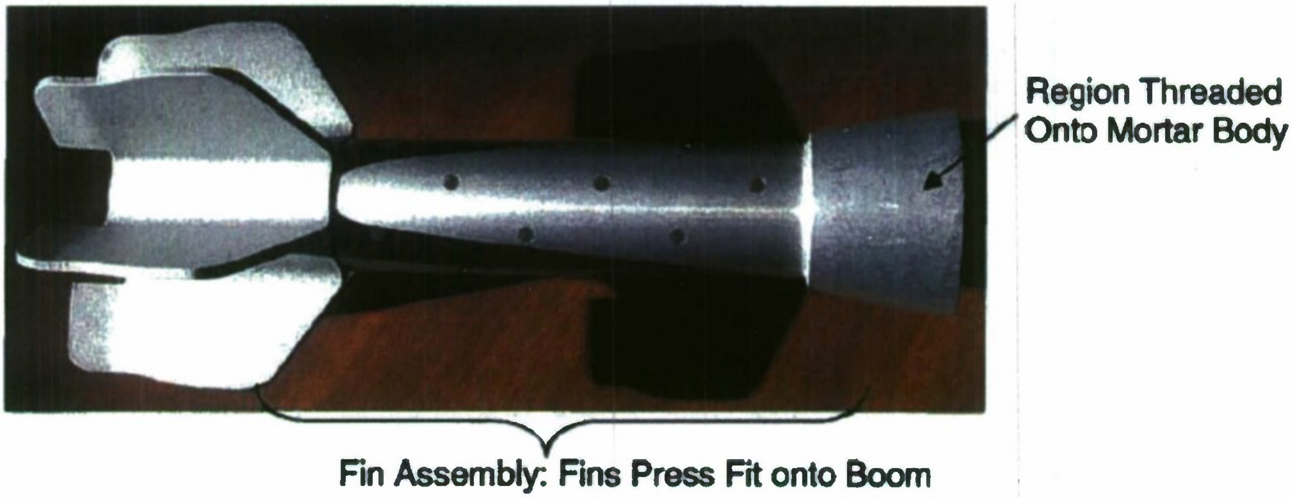

Figure 1
Geometry of the M24 mortar fin

Because the loading condition is threading the fin assembly onto the mortar body, cyclic symmetry is appropriate while plane symmetry is not. Cyclic symmetry simulates a different structure than plane symmetry. In the case of the fin tooling, plane symmetry creates a mirror image that puts the tooling on opposite sides of the fins, this is incorrect. The cyclic symmetry keeps the tooling on the same side of the fins keeping the loads on the correct side (fig. 2). Using cyclic symmetry reduces the size of the model by two thirds.

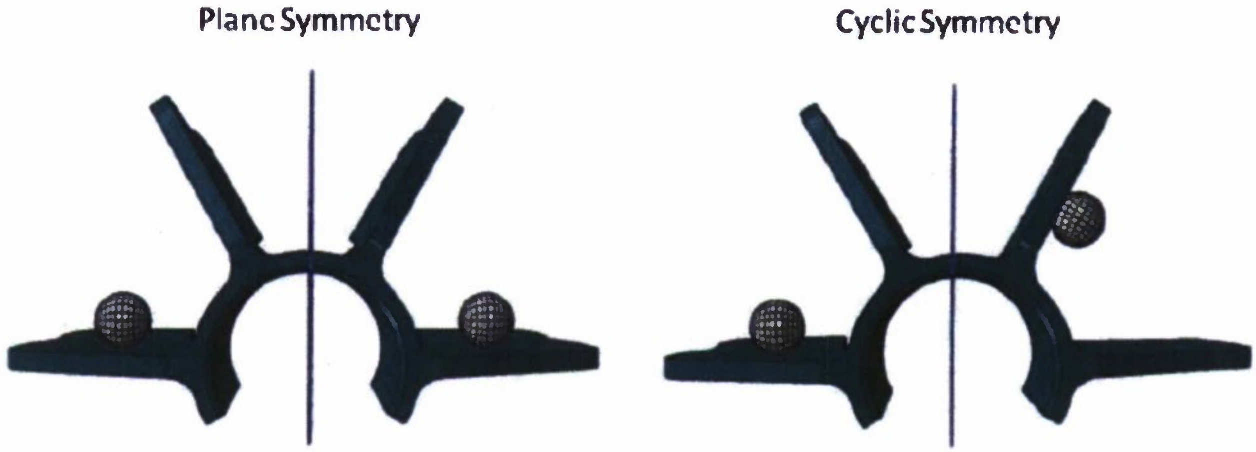

Figure 2
Comparison of plane and cyclic symmetry

For comparison, results using a 360-deg model were compared to results using the cyclic symmetry assumption. One case was completed. Differences in plastic strain predictions were insignificant. The computation cost was reduced by greater than 50% using cyclic symmetry.

BACKGROUND

The Army routinely uses modeling and simulation to increase reliability, functionality, and safety of components. Many analyses involve dynamic modeling and simulations. Lee et al (refs. 1 to 3) has completed simulations to increase reliability under dynamic loading conditions.

Numerous analyses of mortars have been completed to support root cause investigations and reduce the likelihood of future failures. Analysts in the Analysis and Evaluation Technology Division at the U.S. Army Armament Research, Development and Engineering Center (ARDEC), Picatinny Arsenal, New Jersey have used modeling and simulation to investigate the root causes of failures in 120-mm mortar fins (ref. 4), evaluate damage regions in an 81-mm mortar body connected to a structural failure in a mortar tube (ref. 5), estimate the likelihood of a safety critical failure in a 60-mm mortar (ref. 6), evaluate a defect found during production inspections in an M821A2 81-mm mortar (ref. 7), and examine the effect of friction on drop-tests for the M751 81-mm mortar (ref. 8).

METHOD

Overview

This study models the tooling process in an M24 mortar fin to verify that the process will not damage the structure prior to gun shot. The general purpose finite element code Abaqus Standard (ref. 9) was used to model the tooling process. The cyclic symmetry technique in Abaqus, requires the user to first create a model of the repeating sector. Cyclic symmetry is then applied as an interaction. To define cyclic symmetry, the axis of symmetry must be specified, the cyclic boundary surfaces need to be selected, and the total number of repeating sectors must be given. The meshes

on corresponding cyclic boundary surfaces do not need to match. As of Abaqus version 6.10-1, cyclic symmetry can only be used in static, quasi-static, and heat transfer analyses. For this study, a static non-linear analysis was suitable.

The analysis would represent the torque applied when the fins have just been completely threaded on. At that point, the fin assembly would no longer be able to freely twist and the torque would apply stress to the fins, resulting in the highest stress the fins would experience during assembly. Tooling loads were applied on the fins at various distances from the center. Tooling configurations that were further from the center were preferred since they can allow for a reduction in manufacturing cost. However, plastic deformation in the fins away from tool location was unacceptable.

To reduce the computational cost of the analysis, a number of simplifications were used in addition to cyclic symmetry. The tool was modeled as a 7.6-mm (0.3 in.) diameter sphere. The tool was assumed to be rigid. The press fit of the fin onto the housing was omitted. Many other parts of the M24 mortar assembly were not included in the studies to reduce computing time.

Analyses of the different tooling configurations were done with parallel processors on the Army's High Performance Computing Center (HPCC) at ARDEC. The HPCC is a computing cluster consisting of two heads nodes and 144 slave nodes. Each head node is a Dell 2950 containing two dual core 2.66 XEON/em64t processors. Each slave node is a Dell 1950 containing two dual core 2.66 XEON/em64t processors (ref. 10).

Geometry

Figure 3 shows the mortar fin with rigid spheres, simulating the tooling. The geometry for the fin was imported from ProE into Abaqus CAE, the pre-processor software. Once in Abaqus, the geometry was de-featured. The analysis was three-dimensional and cyclic symmetry was used to represent and define the inter-action between the mortar fin and the tooling. Results were modeled for a variety of tooling designs.

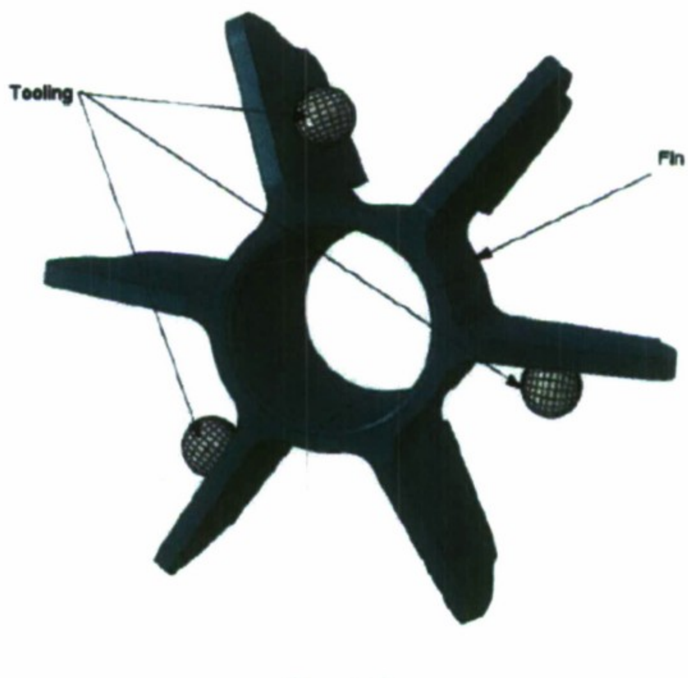

Figure 3
Fin and tooling geometry

Figure 4 shows the cyclic symmetry model. Cyclic symmetry interactions were applied to the cut surfaces of the mortar fin. The tooling was represented by a single rigid ball. Contact was defined between the tooling and fin.

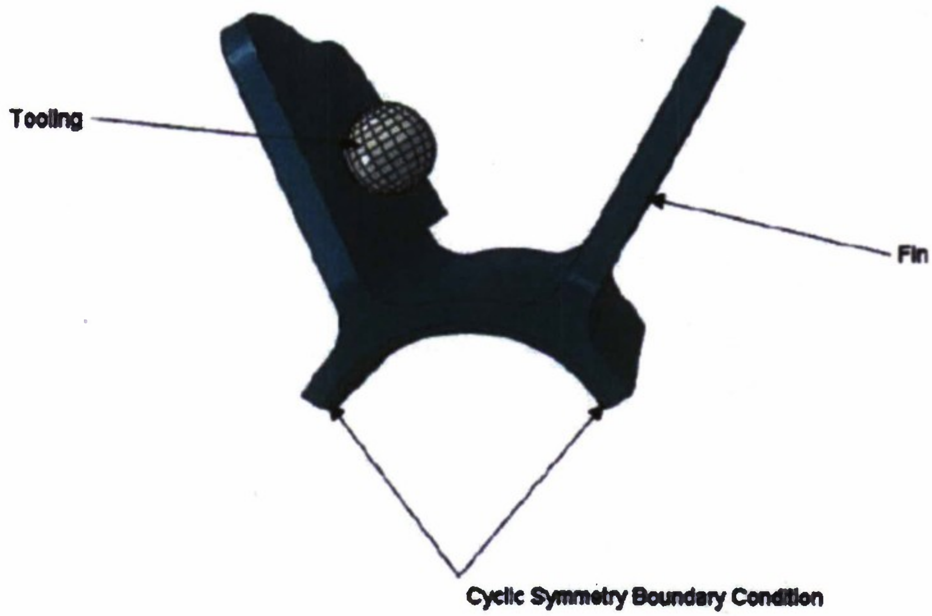

Figure 4
Cyclic symmetry model

The final assembly with the fin and tooling along with the tooling locations are shown in figure 5. Analyses were made with the tooling at five different positions to determine if the tooling would plastically deform the fin in a location away from the contract area.

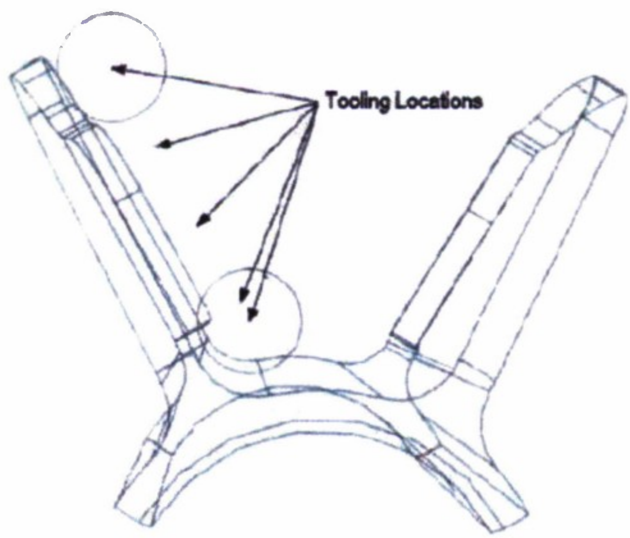

Figure 5
Final assembly of fins with tooling locations

Materials

The parts were modeled as rigid or with a bi-linear elastic/plastic constitutive model. Metal material parameters were taken from the print. A rigid sphere represented the steel head of the tooling. The fins were modeled as 1100 aluminum with a Young's modulus of 68947 MPa (10,000 ksi), a yield strength of 241 MPa (35,000 psi) and a Poisson's ratio of 0.33.

Finite Element Mesh

The fin assembly was modeled using eight-node brick elements. A minimum of four elements were used through the thickness with an approximate seeding of 0.03 of areas of interest and 0.09 in other areas. The cyclic symmetry model had 69,206 finite elements and 488,493 degrees of freedom (DOF). In comparison, a 360-deg model had 212,136 elements and 1,515,774 DOF.

Interactions and Boundary Conditions

The sides of the repeating sector were assigned a cyclic symmetry interaction (fig. 6). To define cyclic symmetry, the "create an interaction button" was selected and the cyclic symmetry option was chosen. Next, the sides of the fin part were selected as the surfaces of the interaction with one side assigned as the master face (red surface in figure 6) and the other face, the slave. Next, two points were chosen to create the axis of symmetry. Lastly, the total number of sections (three) was selected in the dialog box (fig. 7). Other options were accepted as the default.

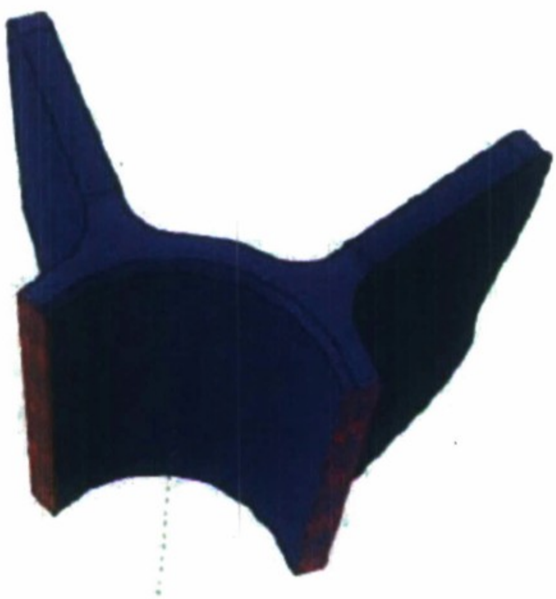

Figure 6
Cyclic symmetry interaction surfaces

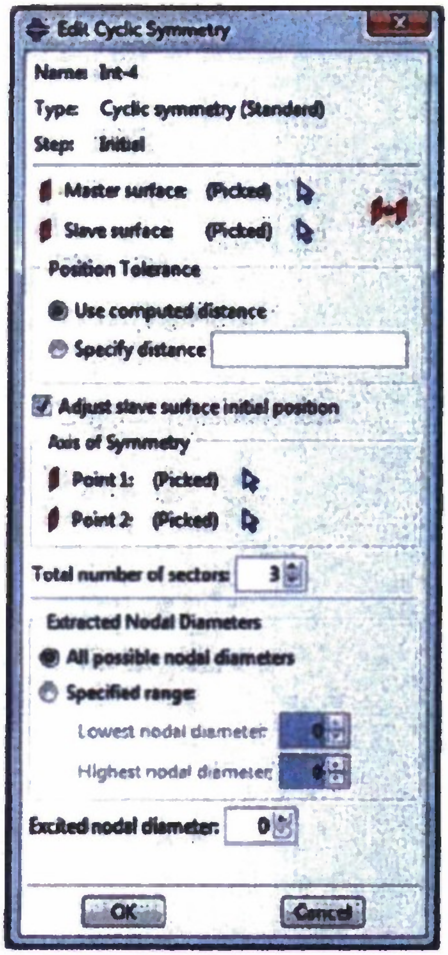

Figure 7
Abaqus 6.10-EF1 cyclic symmetry dialog box

Additional boundary conditions were necessary in this model. The inside radius of the fin part was clamped to represent the highest stress the fins would experience when the fin is already threaded down. Also, the tooling (rigid sphere) was constrained so it could only move into the fin face to apply a force normal to the fin surface.

Loads

Point loads were applied to the rigid sphere to simulate a 33.9-Nm (300 in.-lb) moment when in contact with the fins. The forces applied were varied based on the distance from the center line using the following formula: Force = Moment/Distance (fig. 8).

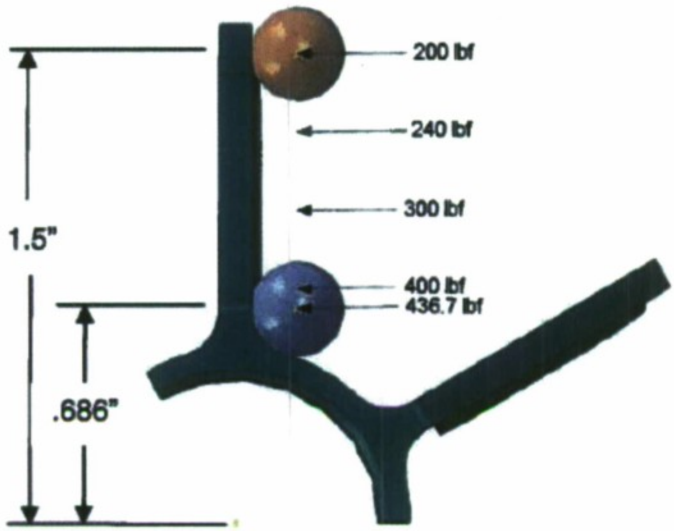

Figure 8
Tooling force at five locations to simulate 33.9-Nm torque

Results

Of the five tooling locations looked at, the furthest from the center the tooling could be located, applying 33.9-Nm (300 in.-lb) of torque, without causing permanent deformation in the fin away from the contact area (where the tool meets the fin), was 19.5 mm (0.75 in.) from the center. Any further, the fins would exhibit plasticity in an unacceptable area (fig. 9).

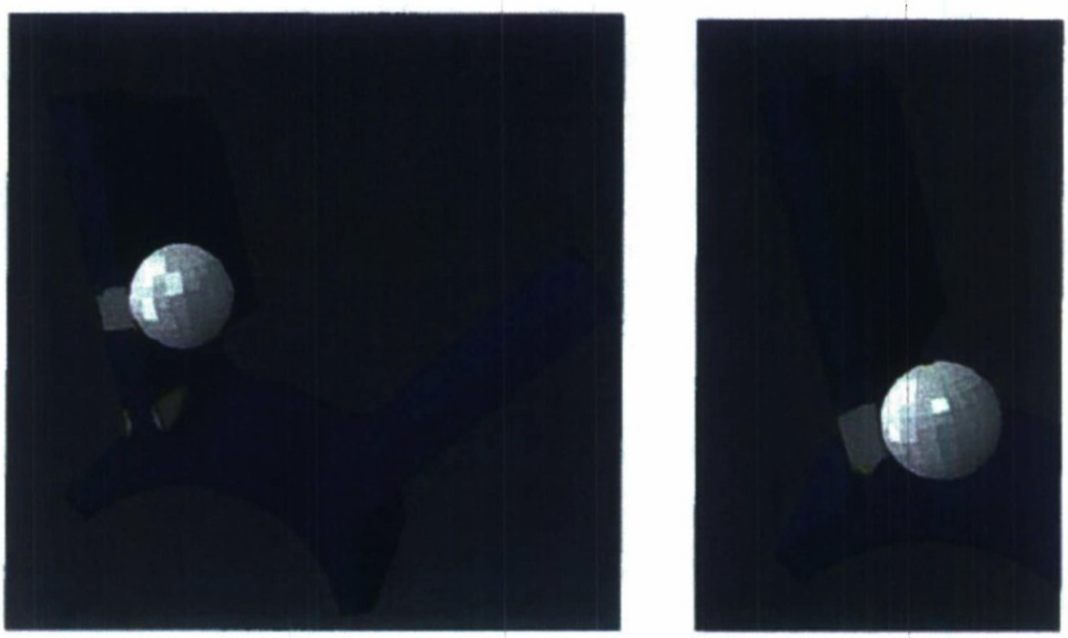

Figure 9
Unacceptable plastic yielding in fin when tool was 25.4 mm from center (left), acceptable plastic yielding in fin when tool was 19.5 mm from center (right)

In other analyses, other levels of torque (19.7 and 39.5 Nm or 175 and 350 in.-lb) were examined, as well as locations closer to the front of the fin and closer to the rear of the fin. Each analysis was based on the same set of assumptions and setup with only the location and force of the tool being changed.

VALIDATION

An analysis of a 360-deg model of the fins and tooling was conducted for one tooling configuration. The configuration chosen used 33.9-Nm (300 in.-lb) torque and a tool contact distance of 25.4 mm (1 in.) from center. This case was used to demonstrate the accuracy of the cyclic symmetry technique and determine the amount of time saved. Plastic yielding results were compared at the junction between the fin protrusion and the center ring (where the plastic yielding would occur away from the contact point). Plastic stains differences are insignificant (fig. 10). These differences may be attributed to slight differences in the mesh.

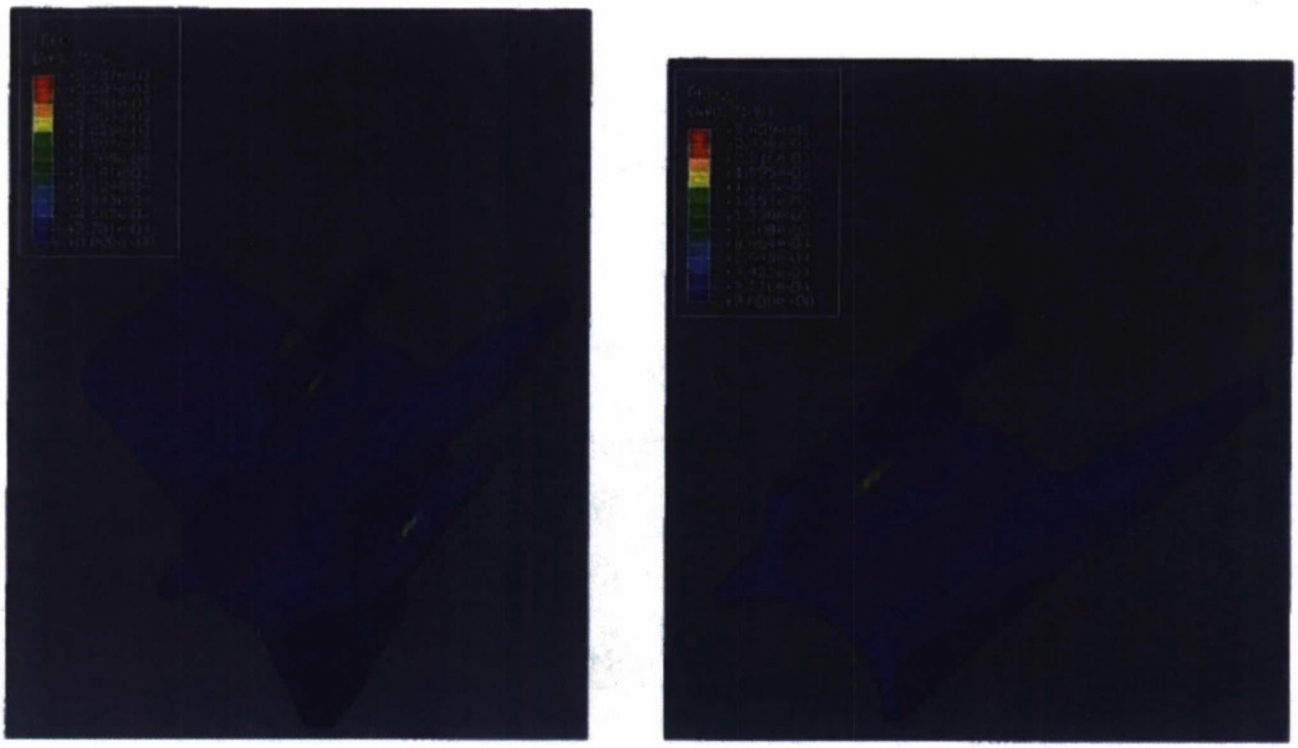

Figure 10
Comparison of equivalent plastic strain (PEEQ) results (at junction between fin protrusion and center ring) between a full 360-deg (left) model and model using cyclic symmetry (right)

The run time in the cyclic symmetry model was compared to the run time in the 360-deg model. Running the analysis on 12 HPCC processors, a full model required 37 min, 27 sec to complete, while a model with cyclic symmetry required 8 min, 44 sec to complete. The run time was reduced by more than half.

CONCLUSIONS

The cyclic symmetry method in finite element analysis makes it possible to solve for the response of a 360-deg structure with cyclic symmetry based on a model of a single repetitive sector. The analysis of assembling the mortar fin was suitable for cyclic symmetry and allowed the model size to be reduced to a third of the original size. The reduction in model size had a negligible effect on the results, but significantly reduced the computer run time required for the analysis to be solved.

In Abaqus 6.10-1, cyclic symmetry is simply an interaction applied to the cyclic symmetry boundary faces. The meshes at the symmetry surfaces do not need to match. With cyclic symmetry, the structure can only undergo cyclic symmetric responses, so only cyclic symmetric loads can be applied.

Determining the furthest the tooling contact points could be positioned from the center without causing unacceptable plastic deformation required multiple simulations. Plastic deformation in the fin at a location away from where the tool was contacting the fin was considered unacceptable. The model of the six finned mortar tail and three pronged tool was reduced using cyclic symmetry to a model of a sector containing two fins and one tool prong. The inside diameter of the fin was clamped to simulate the condition when the fin is fully screwed down, which would be when the fins would be stressed the most during assembly. The furthest the tool contact points could be located away from the center, when applying 33.9-Nm (300-in.-lb) torque, without causing unacceptable plastic deformation was determined by the analysis to be 19.5 mm (0.75 in.). A considerable amount of time was saved by using cyclic symmetry for the iterations testing out all of the different tool contact point locations and torque.

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